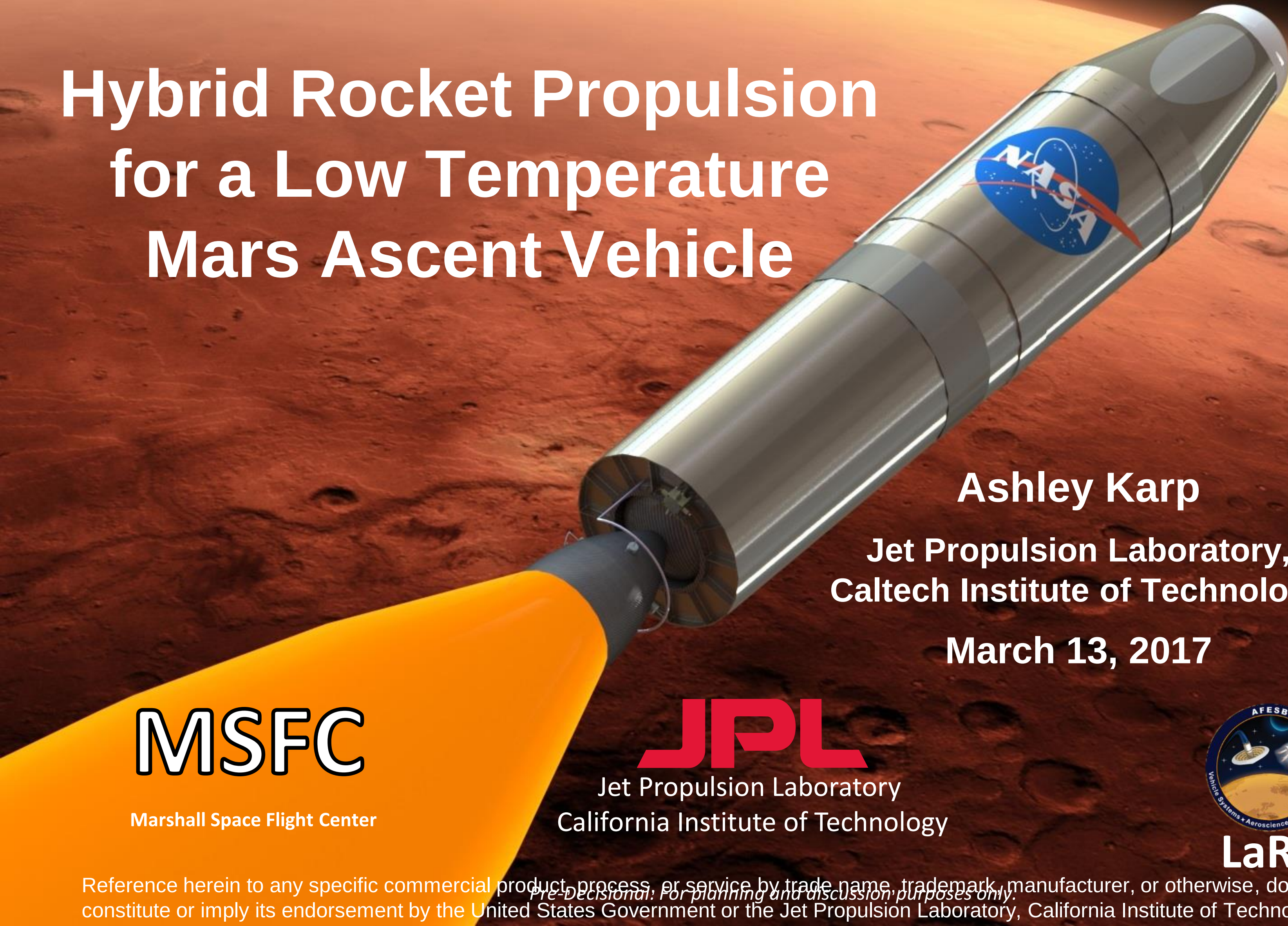
MAV

Mars Ascent Vehicle

Hybrid Rocket Propulsion for a Low Temperature Mars Ascent Vehicle



Ashley Karp

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March 13, 2017

MSFC

Marshall Space Flight Center

JPL

Jet Propulsion Laboratory
California Institute of Technology

AFESB

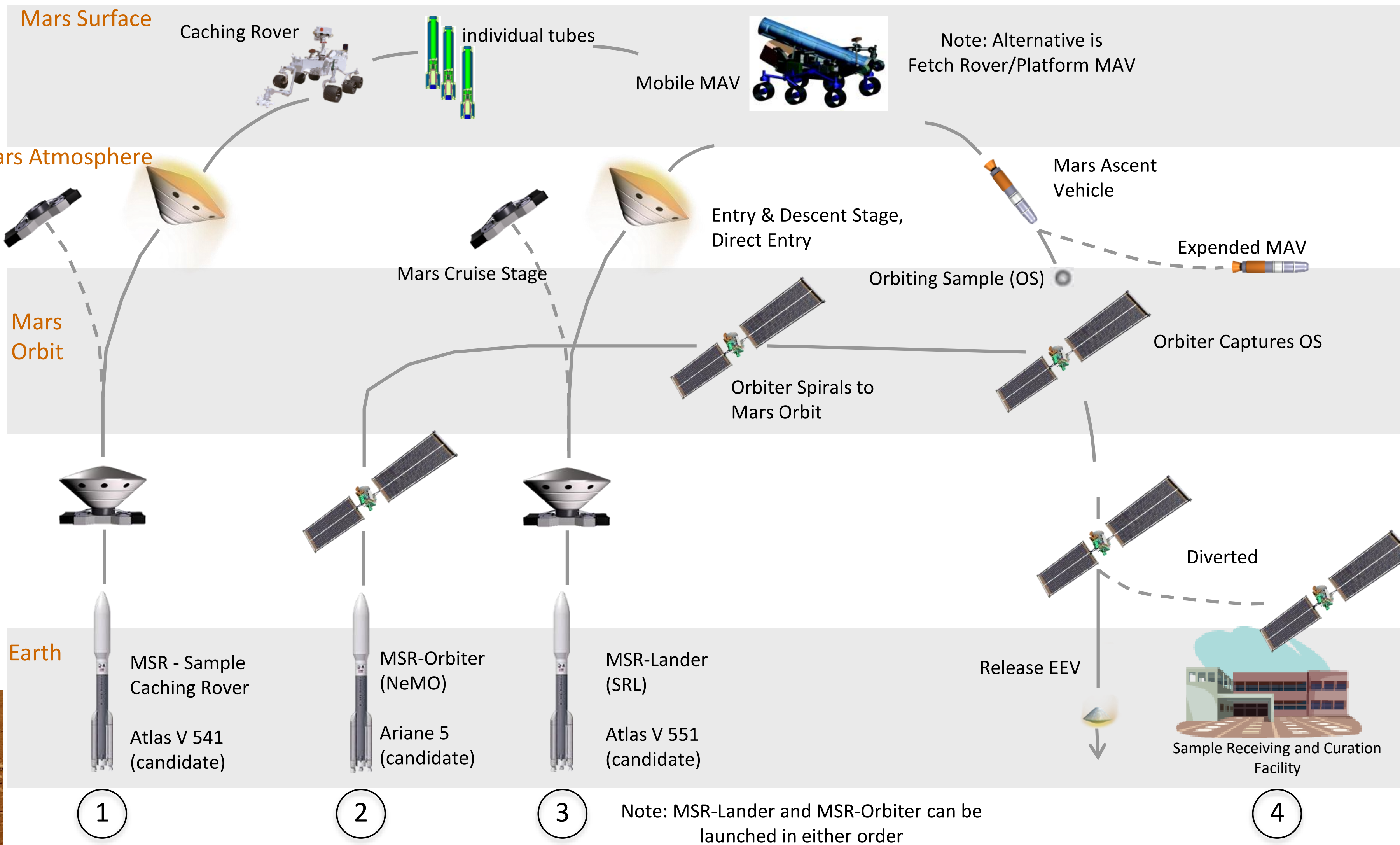
LaRC

Agenda

- Introduction
- Design
- Technology Development
- Challenges
- Future Work
- Summary

MSR Reference Architecture

Mars Ascent Vehicle



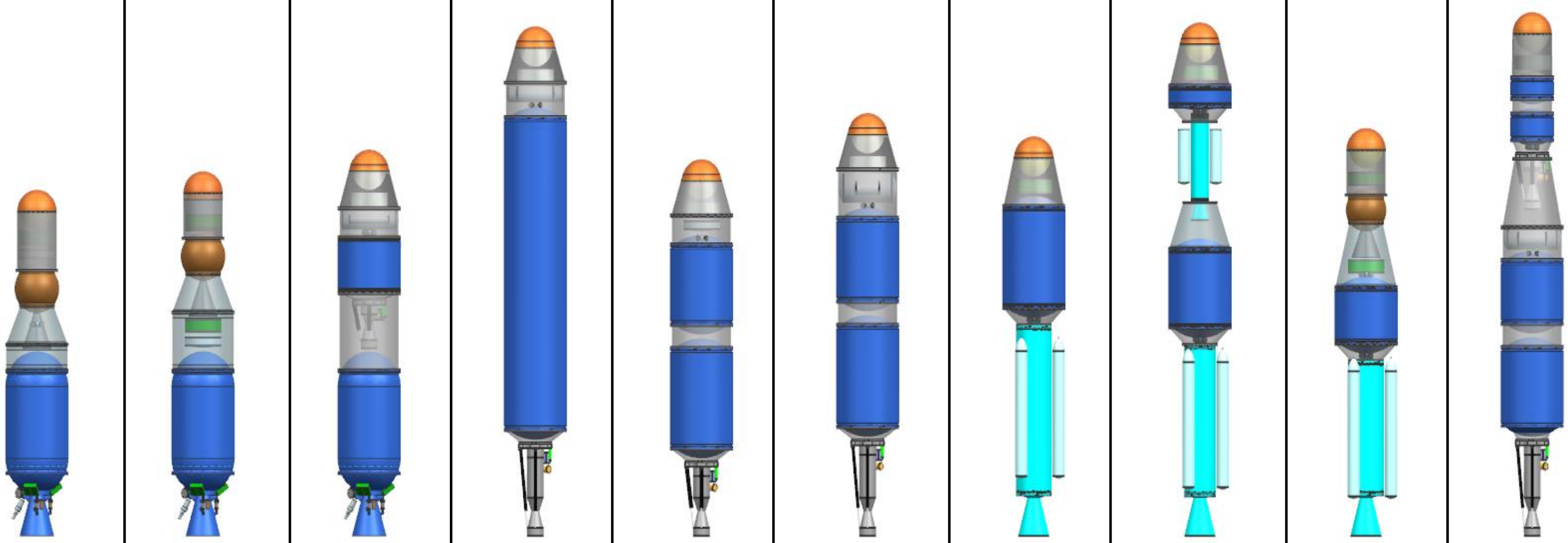
Pre-Decisional: For planning and discussion purposes only.

FY 14 Comparison of Systems

Mars Ascent Vehicle

6.65kg Payload, 20cm Reference OS

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10
	Solid-Solid G-G	Solid-Solid G-U	Solid-Liquid G-G	SSTO Monoprop	SSTO Pump BiProp	SSTO Reg. BiProp	SSTO Hybrid	Hyb-Hyb G-G	Hyb-Solid G-G	BiProp-BiProp G-G



Score	0.60	0.54	0.32	0.52	0.79	0.76	0.76	0.621	0.52	0.57
GLOM	176	158	237	276	182	187	166	173	157	190
Length	1.88 m	1.98 m	2.09 m	2.76 m	2.04m	2.29 m	2.16 m	2.78 m	2.21 m	2.84 m
AFT	-40 C	-40 C	+17 C	+8 C	-37 C	-37 C	-72 C	-72 C	-40 C	-37 C

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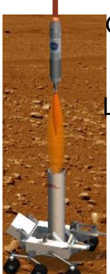
FY 14 Comparison of Systems

Mars Ascent Vehicle

6.65kg Payload, 20cm Reference OS

	Case 1	Case 2	Case 5	Case 6	Case 7
	Solid-Solid G-G	Solid-Solid G-U	SSTO Pump BiProp	SSTO Reg. BiProp	SSTO Hybrid
					
Score	0.60	0.54	0.79	0.76	0.76
GLOM	176	158	182	187	166
Length	1.88 m	1.98 m	2.04m	2.29 m	2.16 m
AFT	-40 C	-40 C	-37 C	-37 C	-72 C



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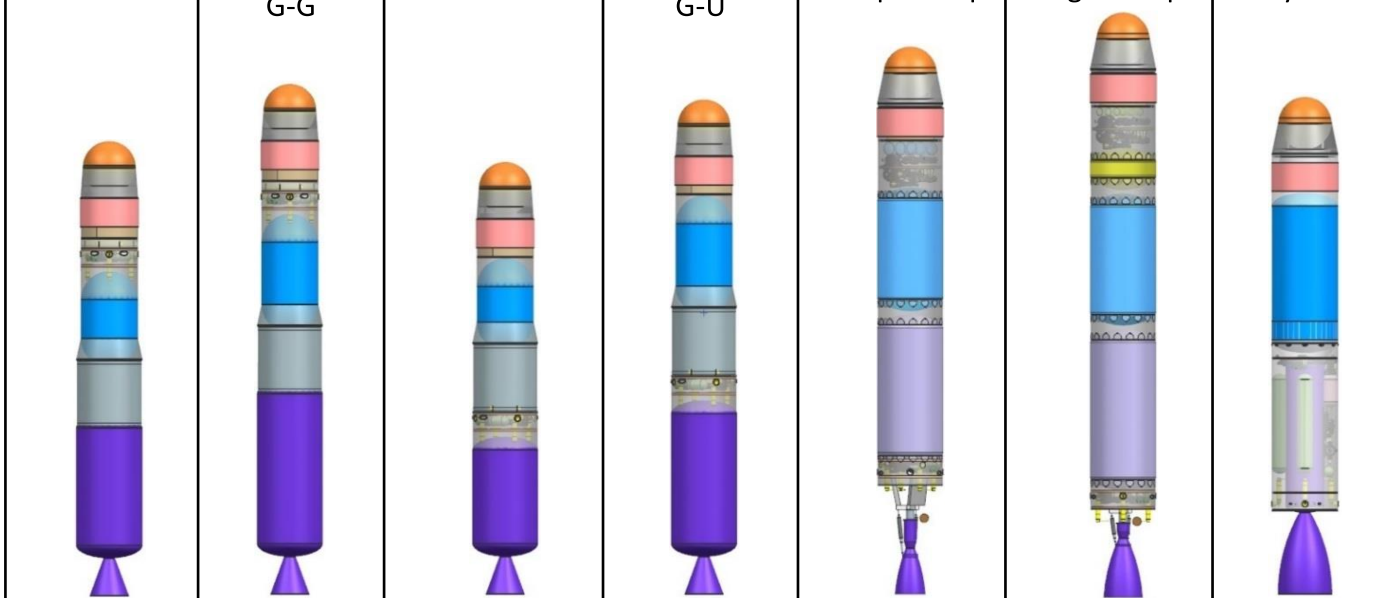
Mars Ascent Vehicle FY 2015 Study

Mars Ascent Vehicle

14 kg Payload, 30 cm Reference OS

	Case 1a	Case 1b	Case 2a	Case 2b	Case 5	Case 6	Case 7
	Solid-Solid G-G	Fixed Solid-Solid G-G	Solid-Solid G-U	Fixed Solid-Solid G-U	SSTO Pump BiProp	SSTO Reg. BiProp	SSTO Hybrid



Payload/OS	**14 kg, 30 cm OS taken as reference**						
GLOM	318.8	341.5	274.1	297.1	255.0	269.8	219.1
Length	2.64 m	2.96 m	2.51 m	2.87 m	3.21 m	3.39 m	2.89 m
AFT	-58 C	-58 C	-58 C	-58 C	-90/-44 C	-90/-44 C	-90/-66 C

(Temp limit if frozen/temp limit if not frozen)

Mars Ascent Vehicle FY 2015 Study

Mars Ascent Vehicle

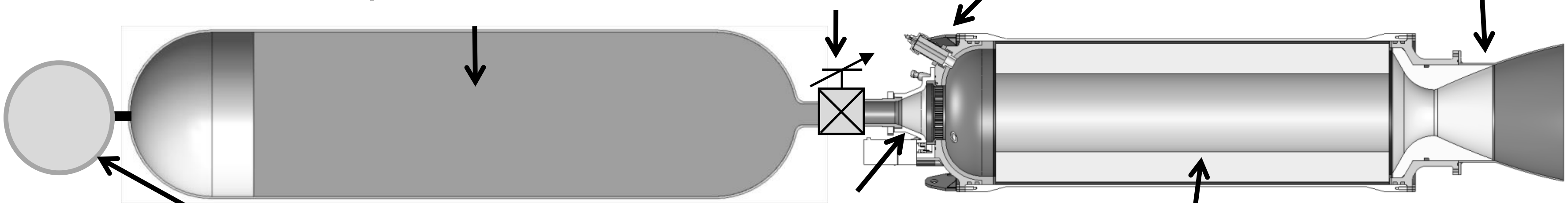
14 kg Payload, 30 cm Reference OS

	Case 7
	SSTO Hybrid 
Payload/OS	
GLOM	219.1
Length	2.89 m
AFT	-90/-72 C

(Temp limit if frozen/temp limit if not frozen)

What is a hybrid rocket?

- Hybrid rockets typically utilize solid fuel and liquid oxidizer.
  - MAV is interested in this option because of its high performance, minimum need for thermal control and capability for multiple starts.

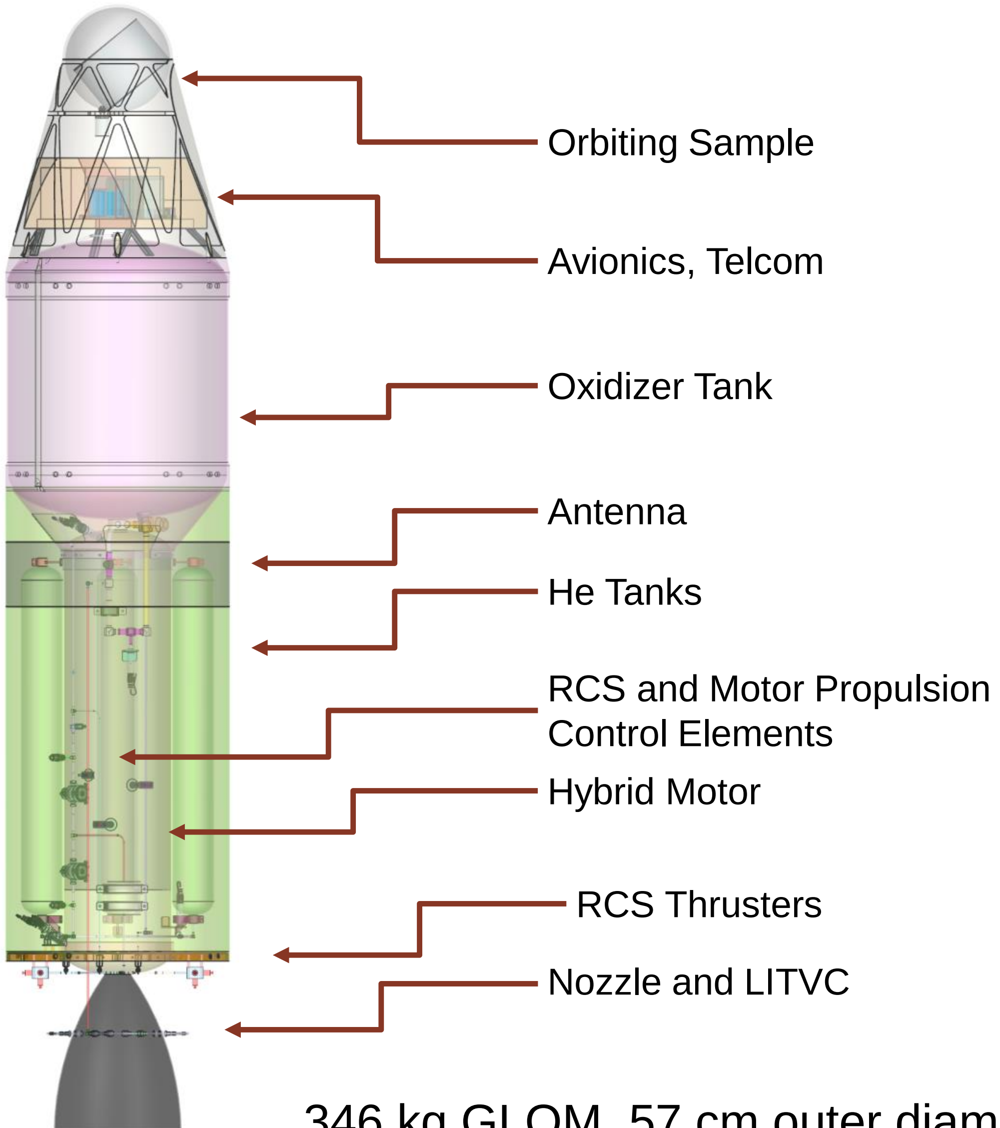


Fuel regression rate → $\dot{r} = aG_{ox}^{n}$ ← Empirically derived constants based on propellant combination

Oxidizer Mass Flux
(mass flow rate of oxidizer divided by the port cross sectional area)

Baseline Concept Overview

Mars Ascent Vehicle



- The current design uses a hybrid propulsion system with ***MON30 (70% N_2O_4+ 30% NO)*** oxidizer and ***SP7, wax-based***, fuel.
- The propellant combination allows for storage temps as low as ***-72 C***, reducing power requirements for an SRL host lander on the surface of Mars.

346 kg GLOM, 57 cm outer diameter, 2.9 m long

Areas of Technology Development

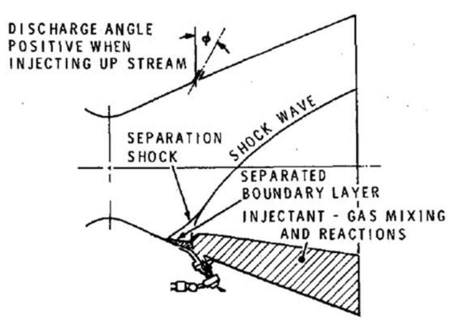
New Hybrid Propellant Combination

- New Propellant Combination
- Hotfire testing
  - SPG
  - Parabilis
  - Whittinghill
- Fuel characterization
- Thermal cycling of fuel cores

Hypergolic Ignition

- Drop testing of MON3 at Penn State and NTO/MON25 at Purdue
- Additional testing at Purdue:
  - SP7 Pellets
  - 2" Rocket

Thrust Vector Control



LITVC system and thrust deflection effects

- Analysis/CFD
- Hotfire testing this year

While the hybrid option showed the most promise, it is also the lowest TRL.

New Propellant Combination

Mars Ascent Vehicle

- Hybrid MAV Propellant Desires:
  - Low temperature capability for fuel and oxidizer to minimize thermal control in route to and on the surface of Mars
  - Operation at low temperature (-20 C)
  - High performance
- Selected propellant combination: SP7/MON
  - SP7 is a wax-based fuel with very good low temperature capabilities, developed by Space Propulsion Group.
  - Mixed Oxides of Nitrogen (N_2O_4 with NO)
    - MON3 is a good, room temperature surrogate for MON30 proposed for flight.

SP7 Wax-based Fuel

+

Mixed Oxides of Nitrogen

MON3 = 0.97 N_2O_4 + 0.03 NO

Hotfire Testing: SPG

- Developed a new wax-based fuel (SP7) specifically for the cold, highly variable Mars environment.
- Completed hotfire testing with N_2O in 2015
- Hotfire testing confirmed predicted regression rate with MON3 in 2016
  - Testing to date covers a little more than half of the actual oxidizer mass flux range
  - Full scale (11”) testing to begin in spring 2017

$$\dot{r} = aG_{ox}^{n}$$

Hotfire Testing: Parabilis

- Full scale (~10”) motor testing attempted at Parabilis.
  - Several short burns were achieved; however injector issues persisted and time ran out before a stable burn was achieved.

PARABILIS SPACE TECHNOLOGIES

Hotfire Testing: Whittinghill

- Whittinghill Aerospace was brought on in 2017 to hotfire test full scale motors.
  - Substantial experience with hybrid motors and LITVC
  - Experience with MON bipropellant engines.

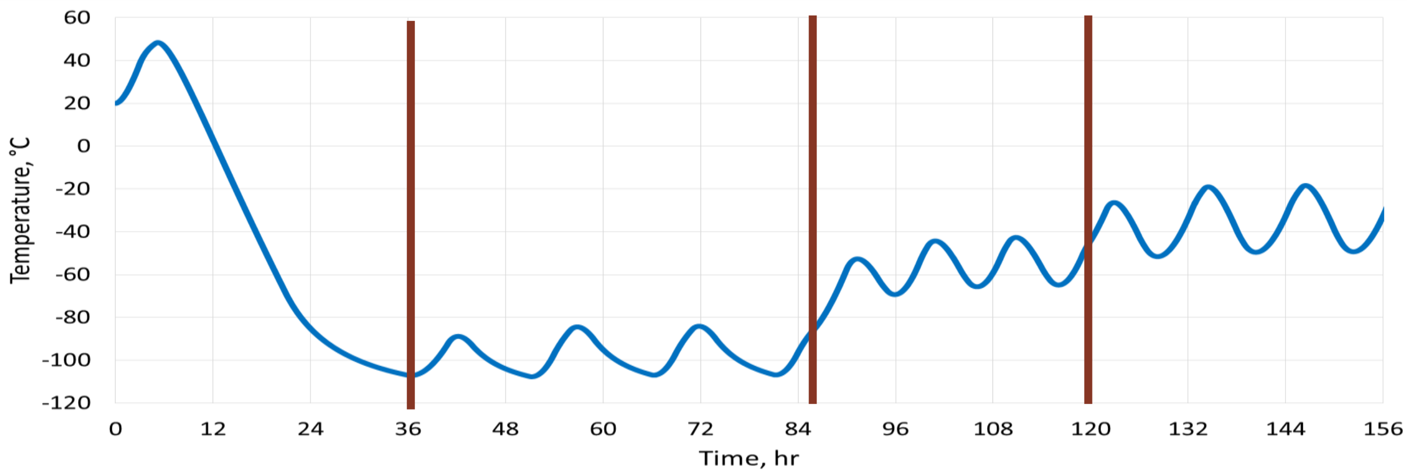
Thermal Cycling of Fuel Core Samples

- Preliminary thermal testing completed at JPL to establish thermal rate limit using 2 samples.
- Completed 201 cycles at MSFC: 1 EDL cycle, 50 winter cycles, 100 spring cycles, and 50 summer cycles
  - 100 day test plan
  - 8 samples: four neat SP7, four aluminized SP7
- Gradient limits in ERD came out of thermal test failures
- Issues:
  - 2.5 inch thick samples, have not completed full length tests
  - b/a of tested samples was 2 instead of 3.
  - Some debonding was observed between the case and the fuel, but no radial cracking under Mars- like conditions.

Thermal Cycling of Fuel Core Samples

MSFC Results: Some debonding (case/core), no radial cracking

EDL Winter Spring Summer

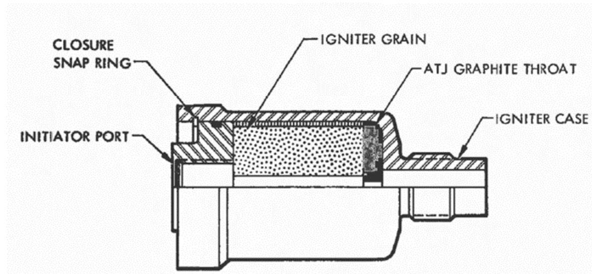


Average Test Results [Test Objectives]	EDL	Winter	Spring	Summer
Max Temperature, °C	40.3 [50]	-82.7 [-90]	-41.9 [-44]	-24.0 [-22]
Min Temperature, °C	-99.3 [-105]	-102.8 [-105]	-56.7 [-64]	-41.8 [-45]
Max Gradient, °C	12.5 [7.0-17.5*]	7.4 [0.9-17.5*]	6.2 [1.8-17.5*]	7.0 [2.3-17.5*]
Max Ramp Rate, °C/hr	7.6 [7.3-10.8]	7.5 [0.8-10.8]	5.9 [1.6-10.8]	6.0 [2.0-10.8]

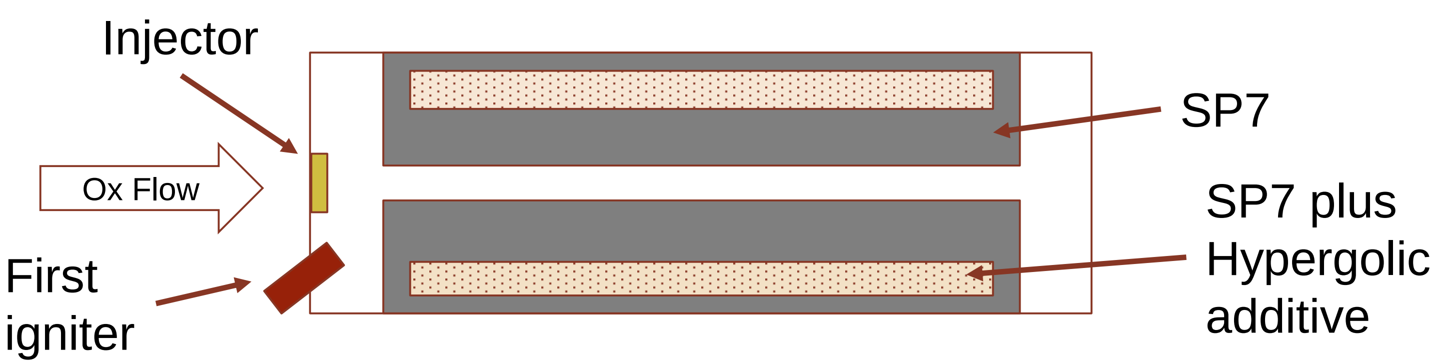
* Max gradient and ramp rate objectives include the range from the predicted gradient to the highest successfully tested gradient or ramp rate.

Ignitors

- First burn ignition utilizes a standard pyro ignitor with redundant NSI’s and fired by the lander PIU.



- Second burn: hypergolic additive in the SP7
  - *Hypergolic, Def: (of a rocket propellant) igniting spontaneously on mixing with another substance.*
  - A SP7 protective layer over the additive layer is envisioned for ground handling/stability



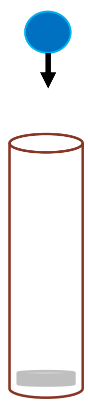
Pre-Decisional: For planning and discussion purposes only.

Search for Hypergolic Additives

- Penn State and Purdue conducted tests to determine additives to the fuel that are hypergolic with MON
- Drivers in the hypergolic testing:
  - It was assumed that additive's reactivity with NTO/MON3 would correlate directly with reactivity with MON30.
    - This is currently being investigated at Purdue with MON25 testing as a follow-on.
  - The additive must be solid
  - It must be hypergolic, not just reactive, with MON3
  - Target of less than 100 ms, ideally closer to 10 ms.

MON Drop Testing and Pellet Testing

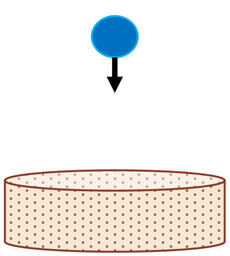
- Penn State and Purdue identified two top candidates with NTO/MON3
  - Purdue is continuing testing with MON-25



H1

H2

- Purdue then mixed H2 with SP7.
  - Hypergolic behavior exhibited with high loading and exposed reactants on surface (representative of second burn).

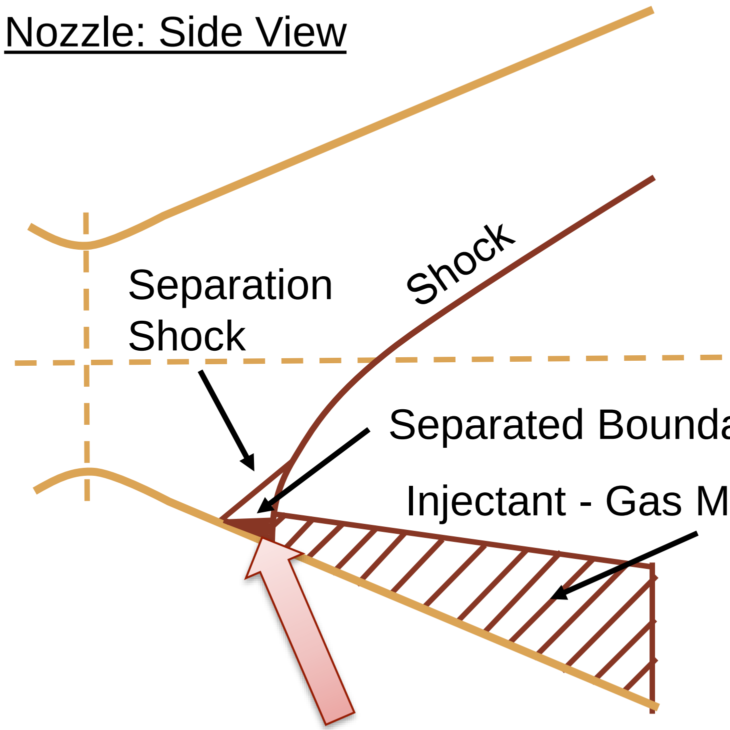


LITVC

Mars Ascent Vehicle

- LITVC Performance is influenced by location of injection point and discharge angle.

Nozzle: Side View



Nozzle: Aft View

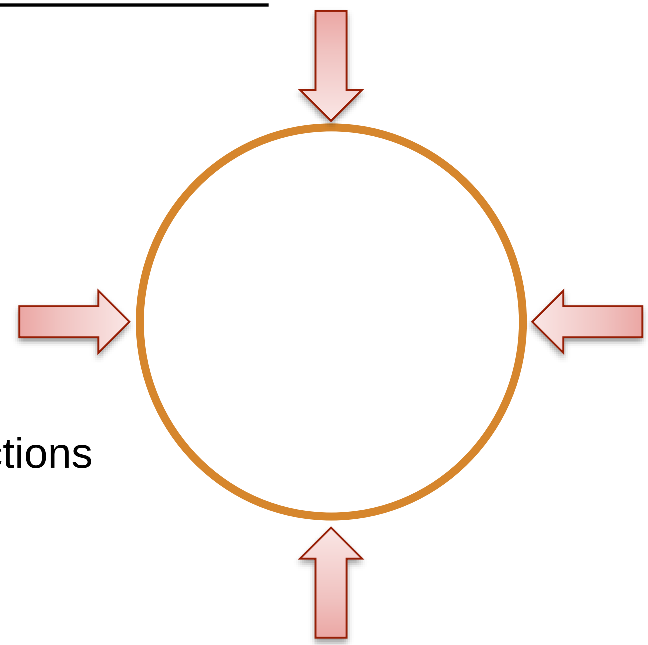
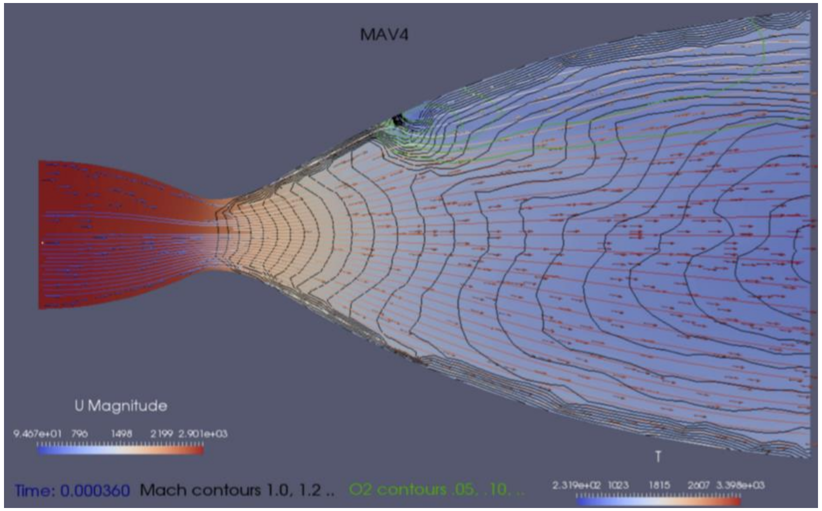


Image adapted from Zeamer, JSC Vol 14 No 6 June 1977 Liquid Injection Thrust Vector Control

LITVC - Whittinghill

- The MON30 relationship was determined based on LITVC tests in different sizes and with different oxidizers. One set of tests with NTO was used to anchor the data.
  - CFD modeling of a MAV motor with LITVC (MON30)
  - The analytical approach was found to over predict the Side Isp when compared to the CFD result, so they were averaged for MON30.
  - Found a relationship for performance, aka “side Isp”
  - From that, can derive the LITVC mass flow rate (MON) and therefore how much propellant is required.



Key Challenges

- There are many challenges to developing a new propulsion system for a potential flagship mission.
- Comparatively low TRL of propulsion system
  - A new fuel formulation was developed to survive the Mars environment and first tests were done in FY15
  - Just started MON testing at the end of FY16
    - Only 8 successful tests so far. Many more to be completed in 2017
    - Only about half of the oxidizer mass flux regime has been investigated so far.
    - No regression rate information from full scale tests yet (will be gathered this year).
- Multiple ignitions
  - Hypergolic ignition has been confirmed in a droplet test environment.
  - Testing in Purdue’s 5 cm motor will confirm the behavior in a more realistic, but still ambient, configuration.
- Operation in the Mars environment
  - CTE thermal mismatch of fuel and liner/case
  - Soakback during coast before second start
- Optimal packaging / configuration
- Ignition/Restart
- Nozzle survivability, TVC and erosion

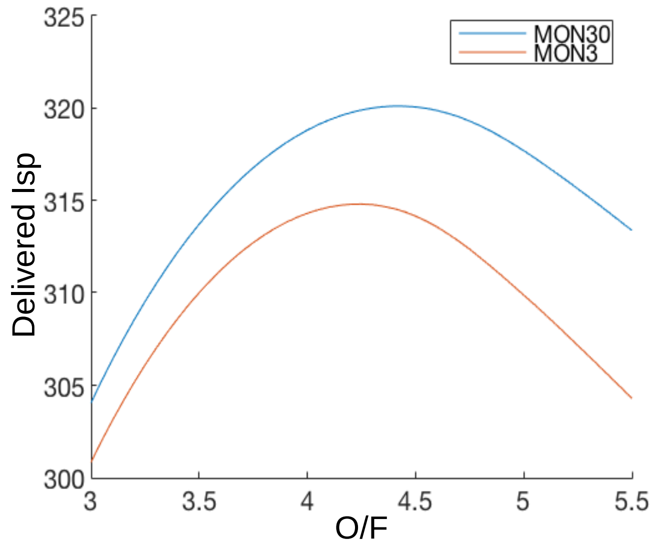
Research is being completed in all of these areas to mitigate the challenges.

Key Challenges

Mars Ascent Vehicle

- Current hotfire testing with MON3 instead of MON30
  - MON3 can be more easily procured and can be used at ambient conditions on Earth.
  - Testing with MON30 during the initial technology development phase is prohibitive from a cost standpoint. MON30 will be considered in 2019.
  - Initial testing with MON3 not only reduces costs, but presents a solution for the MAV if a RTG is used instead of solar panels.

	Changes when moving from MON30 to MON 3
GLOM	0.58%
Thrust	0.44%
Isp	-0.35%
Useable Prop	0.73%
Average O/F	-5.56%
Fuel Core OD	-0.70%
Fuel Core L/D	4.83%
Motor Length	2.66%
Motor Mass	1.35%
Loaded Ox	-0.09%
Loaded Fuel	4.63%
Ox Tank Length	-1.52%
Loaded He	-1.26%



Future Work

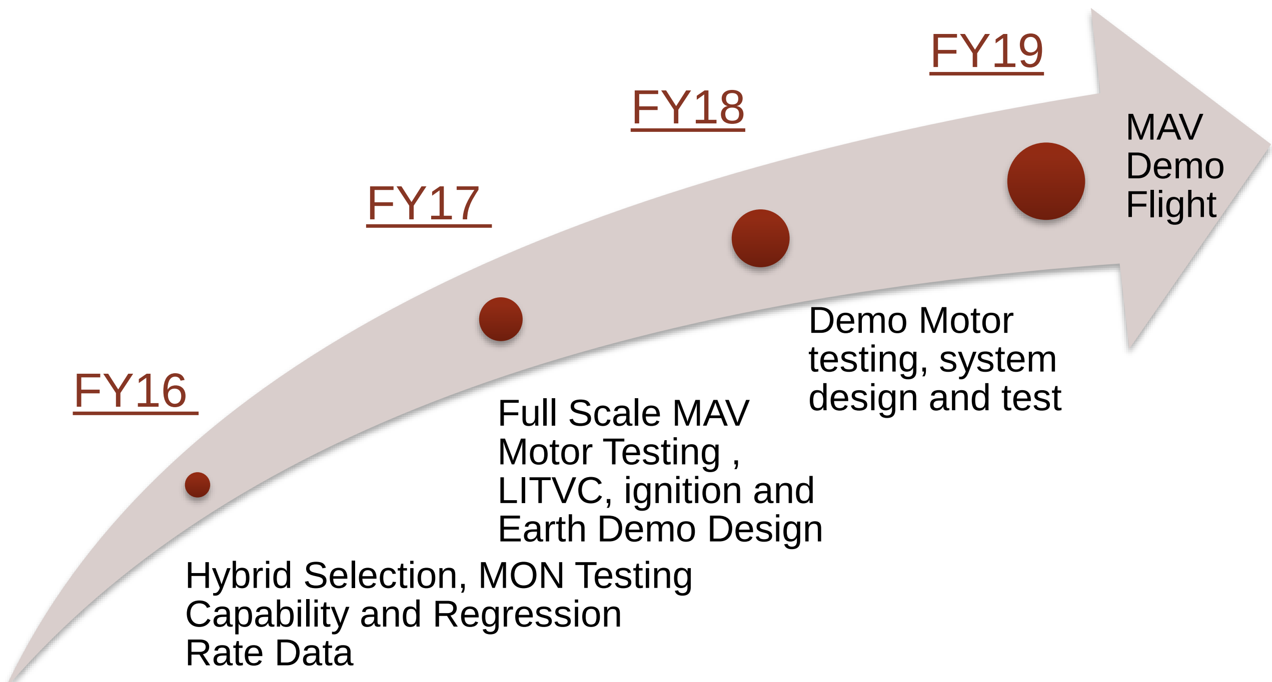
Mars Ascent Vehicle

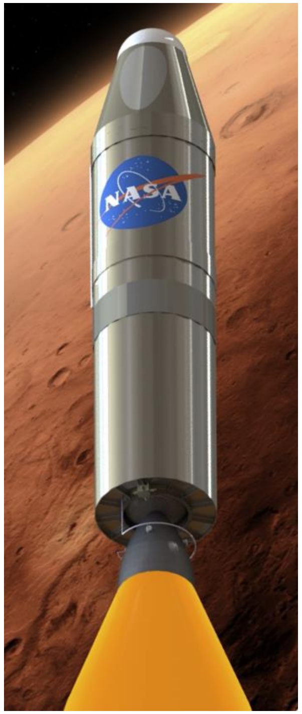
- Completely characterize newly developed fuel (SP7)
  - Hotfire testing with SP7/MON
  - Determine the material properties and processing of SP7 fuel
  - Complete thermal cycling
- Complete study on CTE mismatch of insulator/case and fuel grain
- Ignition testing
  - Hypergolic ignition method strongly desired
  - Quantify the amount of heat needed to ignite the hybrid.
- Nozzle and TVC testing

Path Forward – Proposed Demo Launch

Mars Ascent Vehicle

- Technology development to culminate with Earth-based demonstration flight
  - Earth-based launch of a hybrid MAV is currently in the planning stages, target mid FY2019
  - Target to match most Mars parameters with Earth-based flight
  - Goal is overall risk reduction for future MAV system





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Summary

- A wax-based fuel/MON30 hybrid propulsion system is capable of meeting the requirements of a Mars Ascent Vehicle.
- Substantial technology investment is ongoing to develop hybrid propulsion technology for this application (currently TRL 3)
- Full scale testing in FY17 will raise the TRL to 4.
- Major Accomplishments in FY16:
  - First successful tests with SP7/MON3: high regression rate fuel and storable oxidizer. Data is tracking the predictions very well.
  - Multiple solid additives found to be hypergolic with MON.
  - One additive was shown to be hypergolic with MON while mixed into SP7.
  - Preliminary LITVC performance/usage equation has been determined.

- ***While several technological challenges remain, significant development and risk mitigation has already been accomplished in this short time period.***

Questions?

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Government sponsorship acknowledged.

Classical Hybrid Combustion

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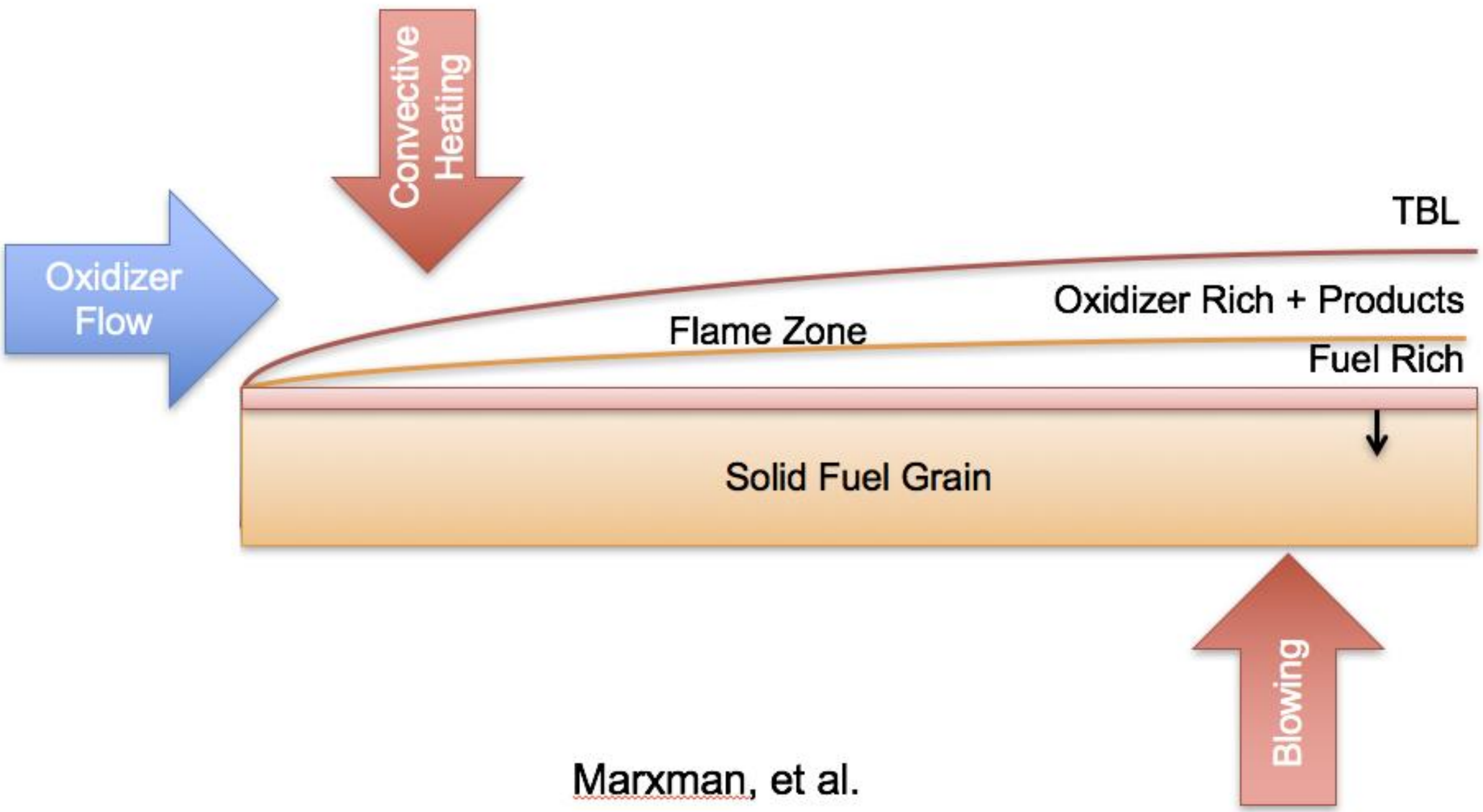
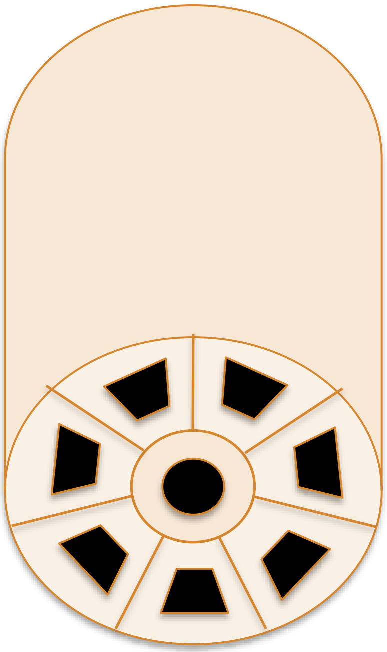
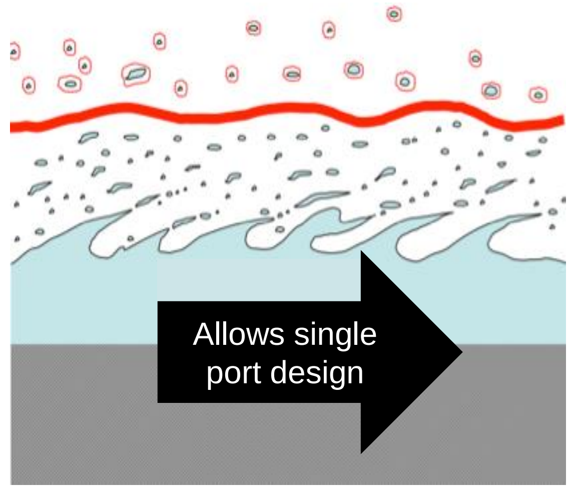
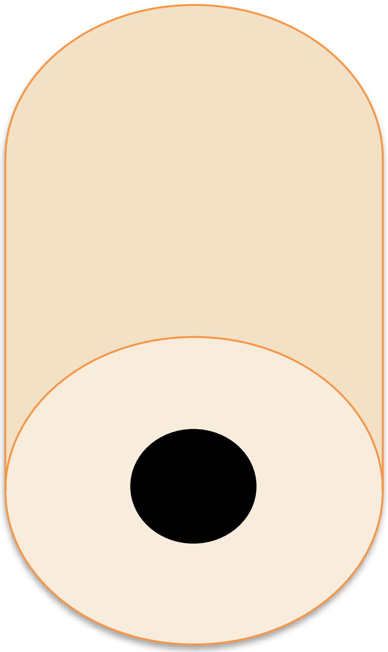


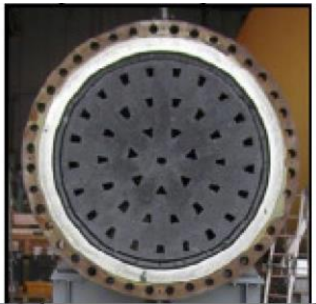
Evolution of Hybrid Rockets

Mars Ascent Vehicle

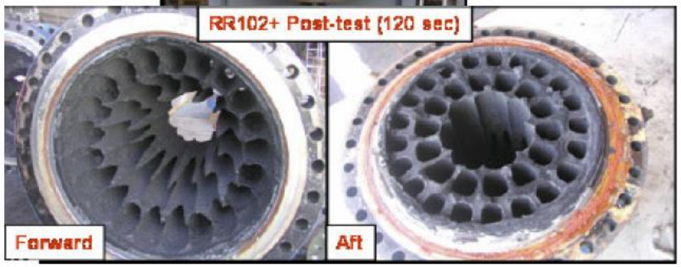








Lockheed Martin 2006 Multiport Test
Source: Karabeyoglu, 2012



Peregrine Motor Test, NASA Ames, Source: Aerospace America 2011.